Multibody Model for Planetary Gearbox of 500 kW Wind Turbine

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Publication date:
2013

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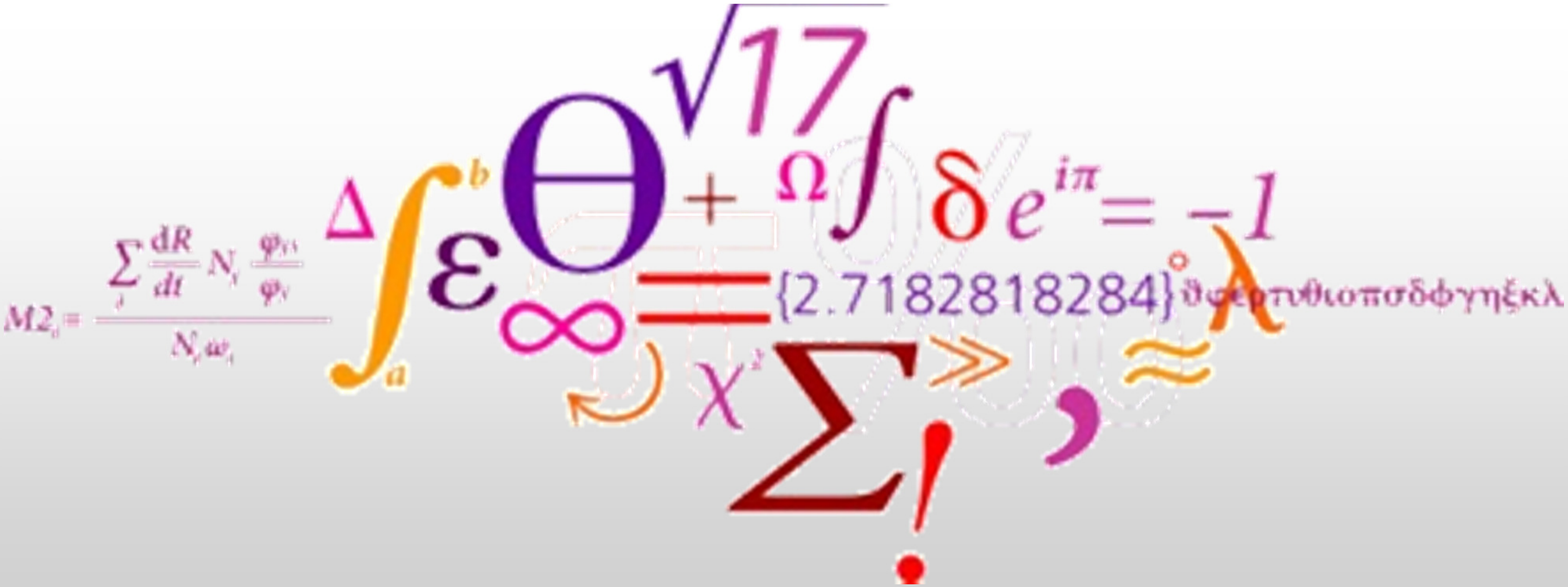
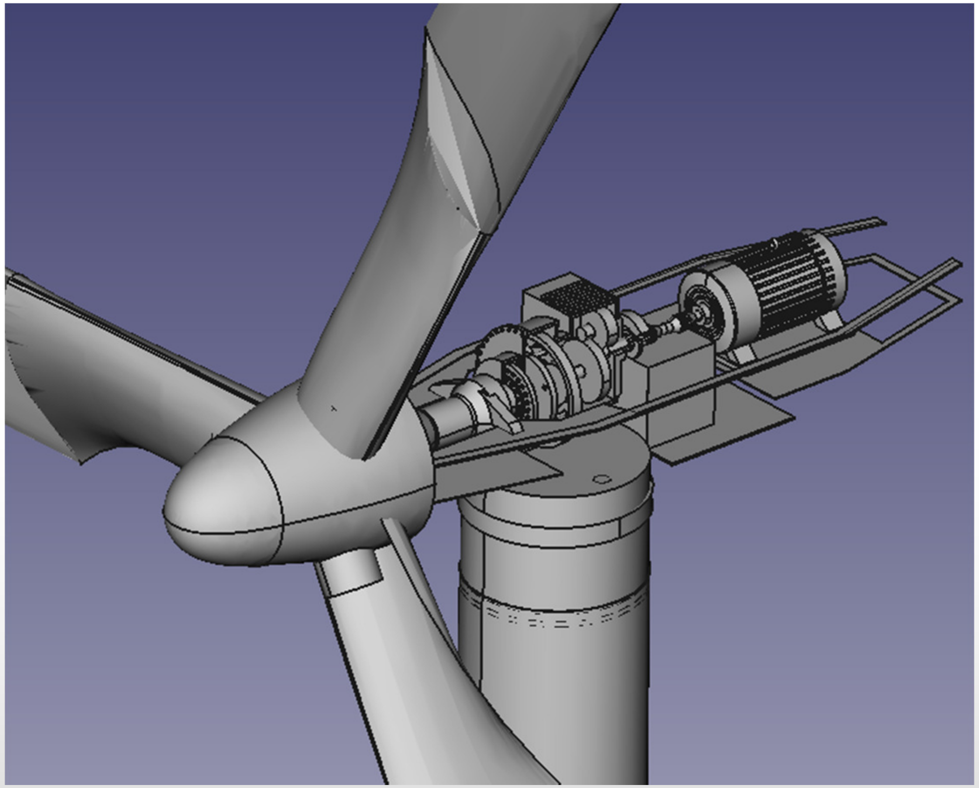


DTU Mechanical Engineering

Overview / topics

1. Introduction
2. Aeroelastic model (FLEX 5)
3. Experiments vs. simulations
4. Multibody model - description
5. Results
6. Conclusions



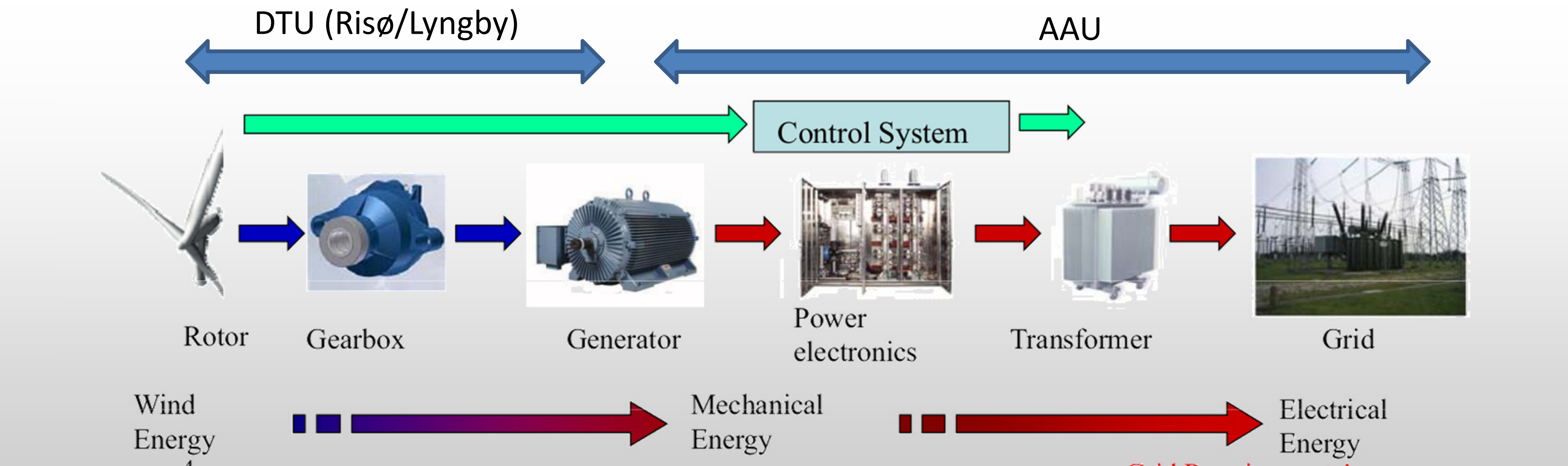
1. Introduction

Objective:

To create a multibody program for modelling drivetrain loads, forces etc on main components such a bearings and all stages in the gearbox.

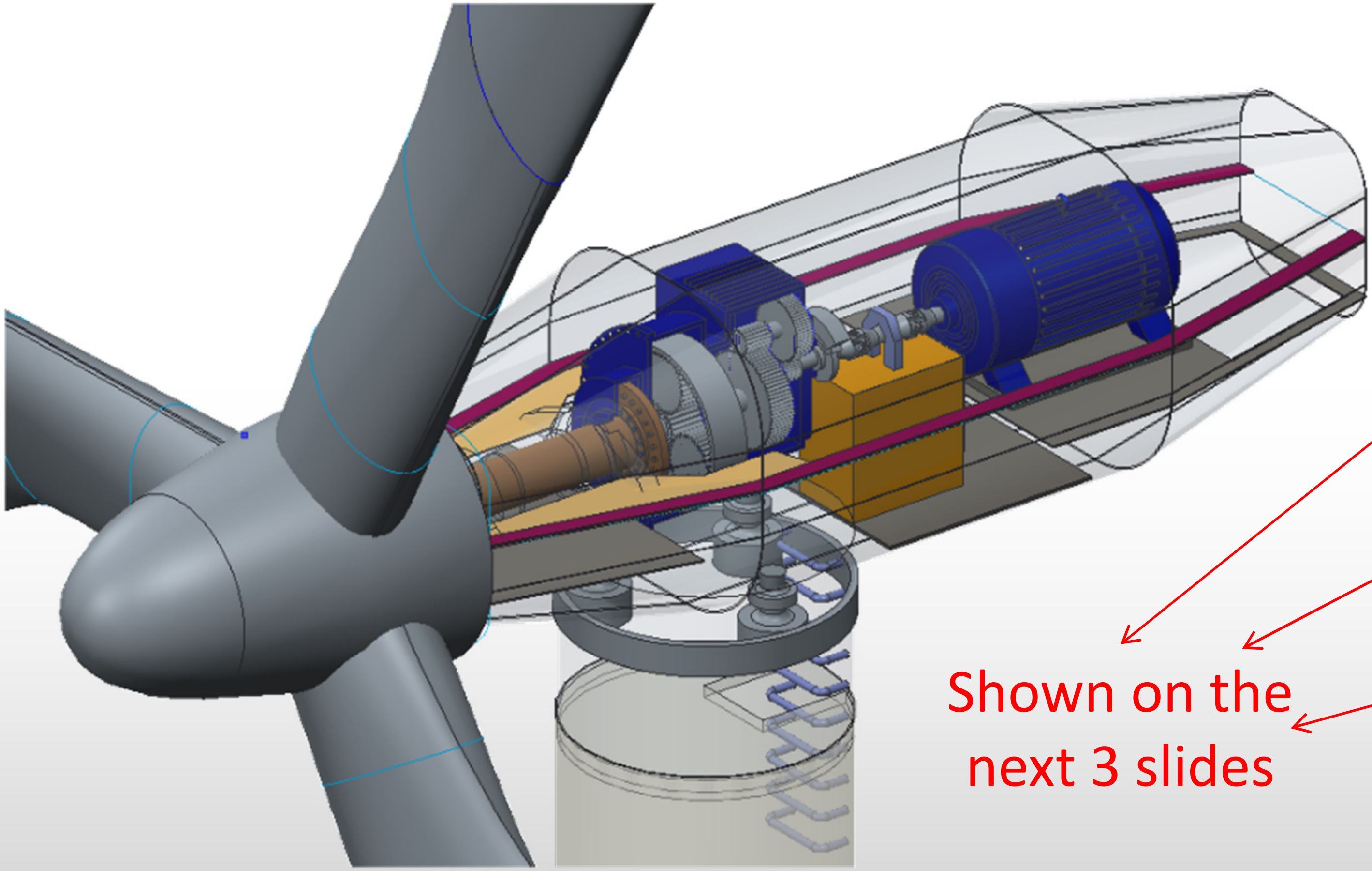
Method:

Matlab code with input for generator and rotor loads from FLEX5, using a complete structural model of the windturbine.

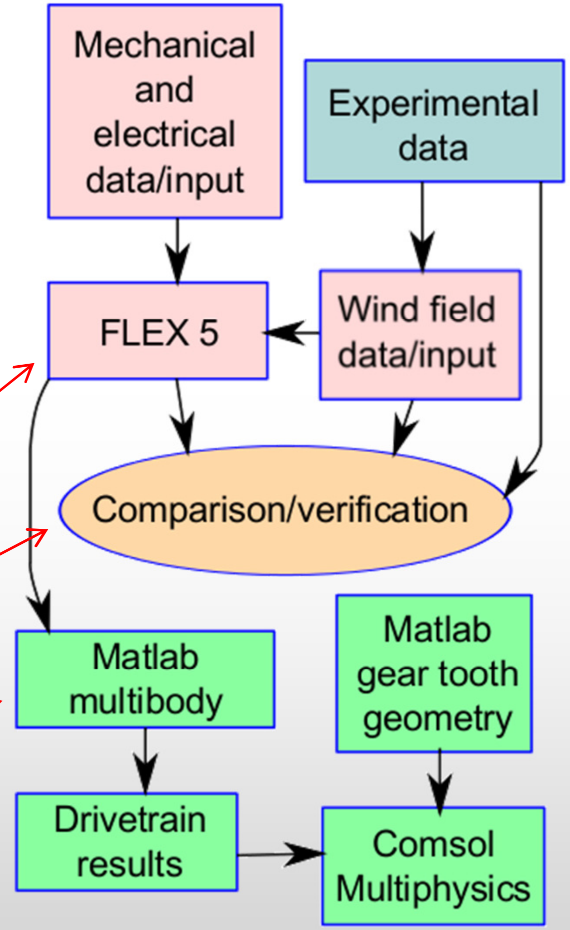


1. Introduction

"Multibody drivetrain model of a 500 kW wind turbine for predicting gear tooth stresses in a planetary gearbox" – methods:



Shown on the next 3 slides

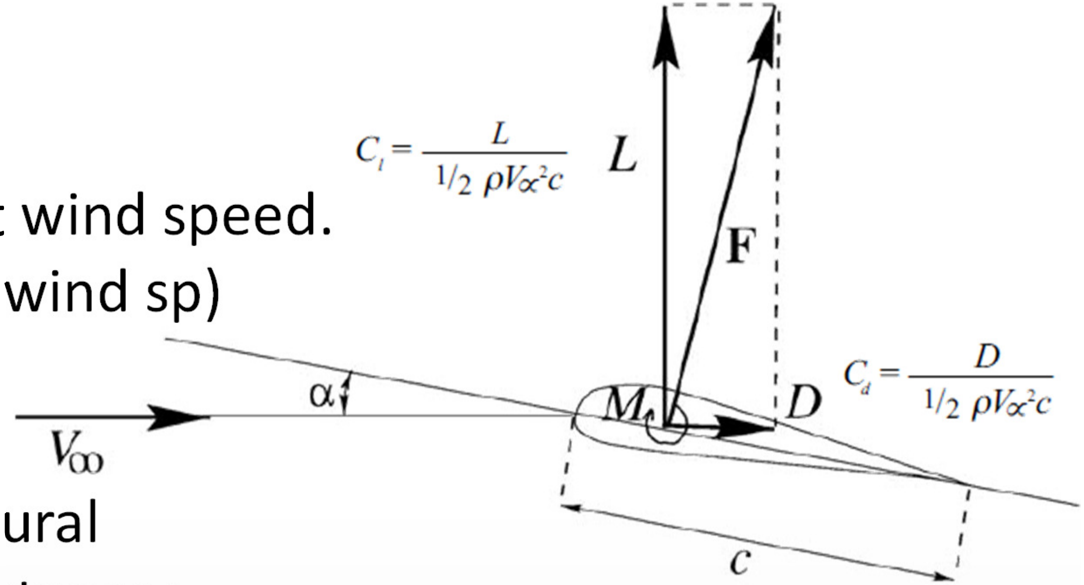


(a) Illustration of rotor, nacelle, main shaft, gearbox (planetary + 2 parallel stages), brake, 500 kW generator, 3 yaw motors etc.

(b) Outline of method used.

2. Aeroelastic model (FLEX 5)

a) Input:
   a) - ”Real” athmospheric turbulent wind speed.
   - Wind field (based on TI+mean wind sp)
   - Blade aerodynamic data: Lift+
   Drag coefficients, radial stations
   - Elastic properties, mass, structural
   damping, (bending) stiffness, distances,
   generator data (mass, moment of inertia, slip, loss/efficiency)



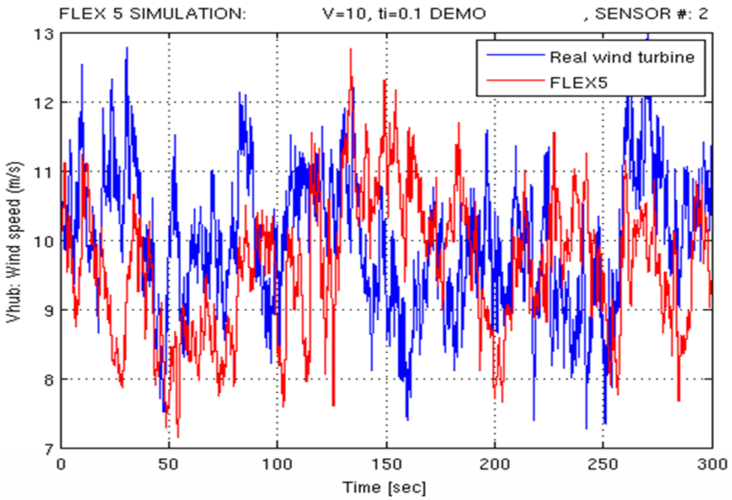
$$\mathbf{M\ddot{x} + C\dot{x} + Kx = F_g}$$

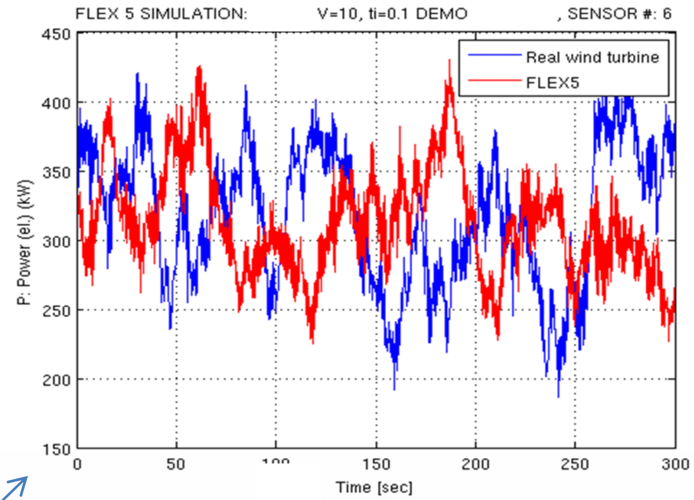
b) Output:
   Main shaft/generator torque, rotor/blade forces, displacements etc.

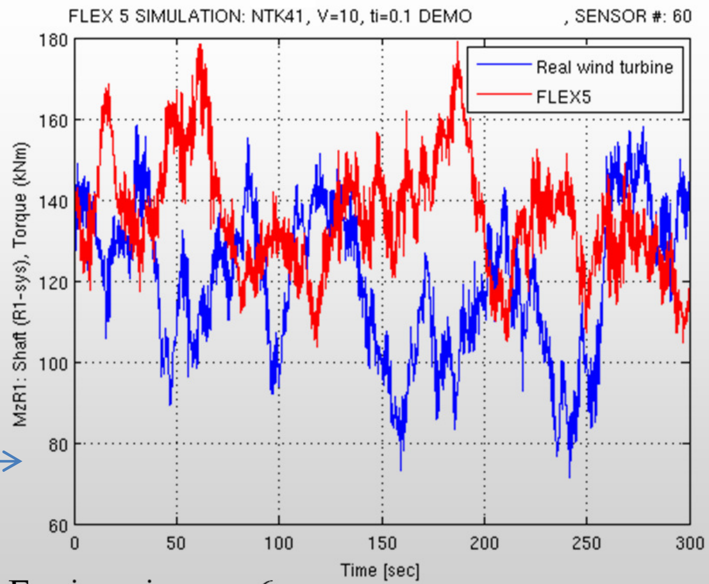
2. Aeroelastic model (+ validation: winddata.com)

FLEX5
Input

FLEX5
Output





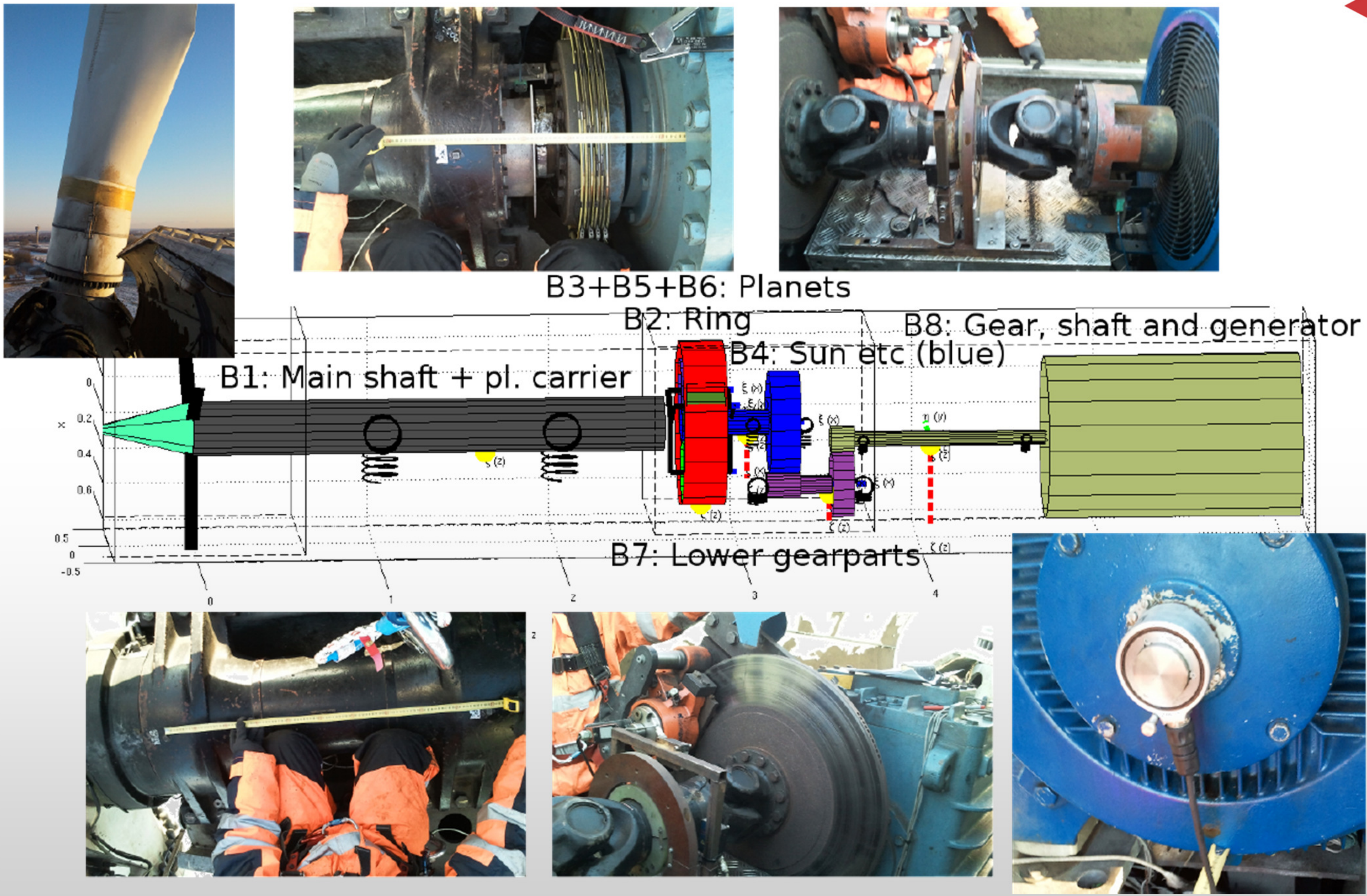


Wind speed (m/s)

Power (kW)

Main shaft torque (kNm)

4. Multibody model – bodies and constraints



4. Multibody model – bodies and constraints

For a constrained mechanical system with m independent constraints

Algebraic constraints $$\mathbf{\Phi} = \mathbf{0} \tag{9.51}$$

the velocity and acceleration equations are

$$\mathbf{\Phi}_{\mathbf{q}}\dot{\mathbf{q}} = \mathbf{0} \tag{9.52}$$

and

Diff. eq.

$$\mathbf{\Phi}_{\mathbf{q}}\ddot{\mathbf{q}} - \boldsymbol{\gamma} = \mathbf{0} \tag{9.53}$$

The equations of motion for this constrained system are as given in Eq. 9.6:

Force equilibrium $$\mathbf{M}\ddot{\mathbf{q}} - \mathbf{\Phi}_{\mathbf{q}}^{T}\boldsymbol{\lambda} = \mathbf{g} \tag{9.54}$$

Equation 9.53 can be appended to Eq. 9.54 and the result can be written as

Eq. of motion: $$\begin{bmatrix} \mathbf{M} & \mathbf{\Phi}_{\mathbf{q}}^{T} \\ \mathbf{\Phi}_{\mathbf{q}} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{q}} \\ -\boldsymbol{\lambda} \end{bmatrix} = \begin{bmatrix} \mathbf{g} \\ \boldsymbol{\gamma} \end{bmatrix} \tag{9.55}$$

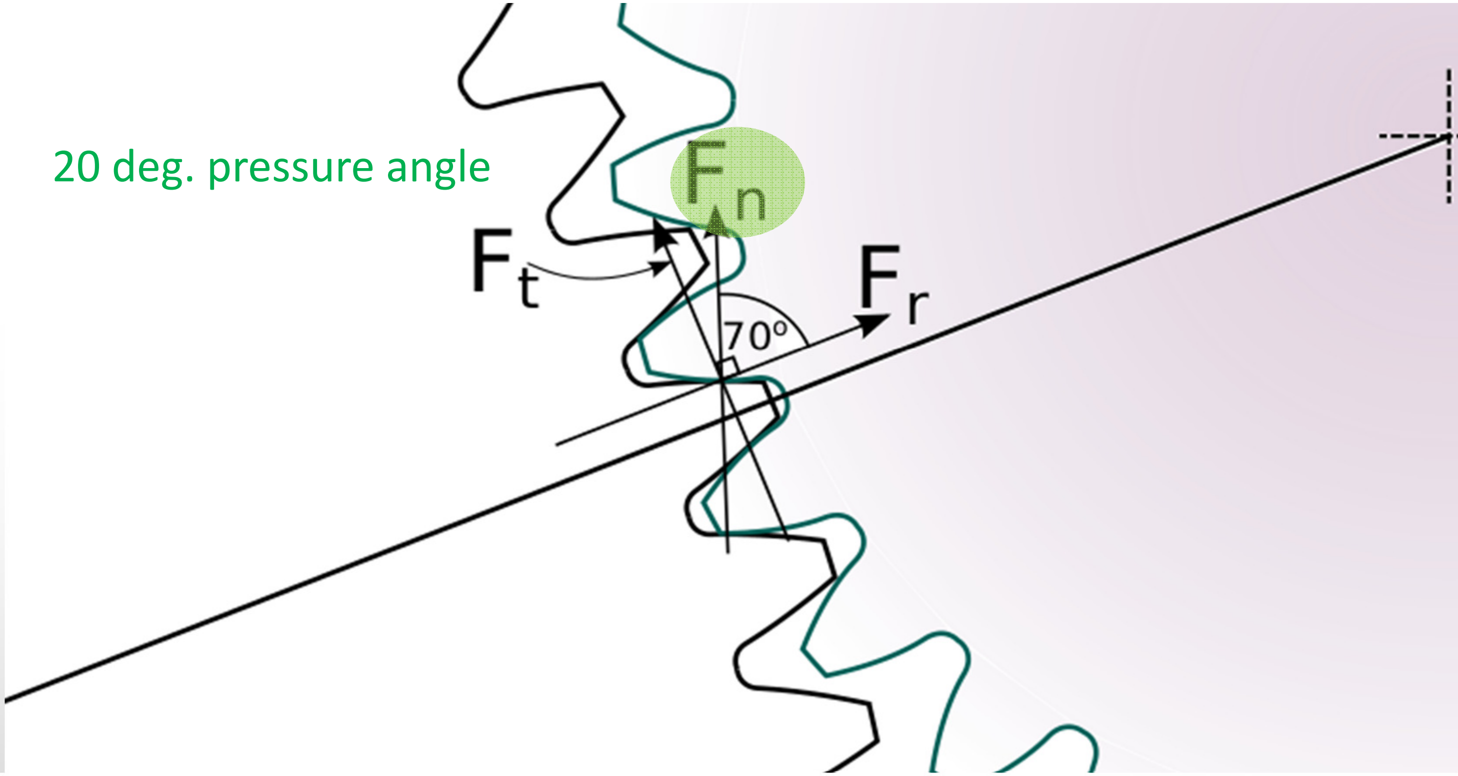
Convert 2nd order Initial Value Problem → Two 1st order ODEs:
ODE45 in Matlab to integrate and get velocities and positions

4. Multibody model – bodies and constraints

$$\dot{\Phi} : (A_{70} \cdot v_r)^T \left(\begin{Bmatrix} \dot{x_1} \\ \dot{y_1} \end{Bmatrix} + r_{p1}(\omega_1 \hat{v}_r) \right) - (A_{70} \cdot v_r)^T \left(\begin{Bmatrix} \dot{x_2} \\ \dot{y_2} \end{Bmatrix} - r_{p2}(\omega_2 \hat{v}_r) \right) = 0$$

2D gear constraint equation

20 deg. pressure angle



$$\ddot{\Phi} : (A_{70} \cdot \dot{v_r})^T (\dot{r_1} + r_{p1}\omega_1 \hat{v}_r) + (A_{70} \cdot v_r)^T \left(\ddot{r_1} + r_{p1}\dot{\omega_1}\hat{v}_r + r_{p1}\omega_1 \dot{\hat{v}}_r \right)$$
$$-(A_{70} \cdot \dot{v_r})^T (\dot{r_2} - r_{p2}\omega_2 \hat{v}_r) - (A_{70} \cdot v_r)^T \left(\ddot{r_2} - r_{p2}\dot{\omega_2}\hat{v}_r - r_{p2}\omega_2 \dot{\hat{v}}_r \right) = 0$$

4. Multibody model – equations of motion

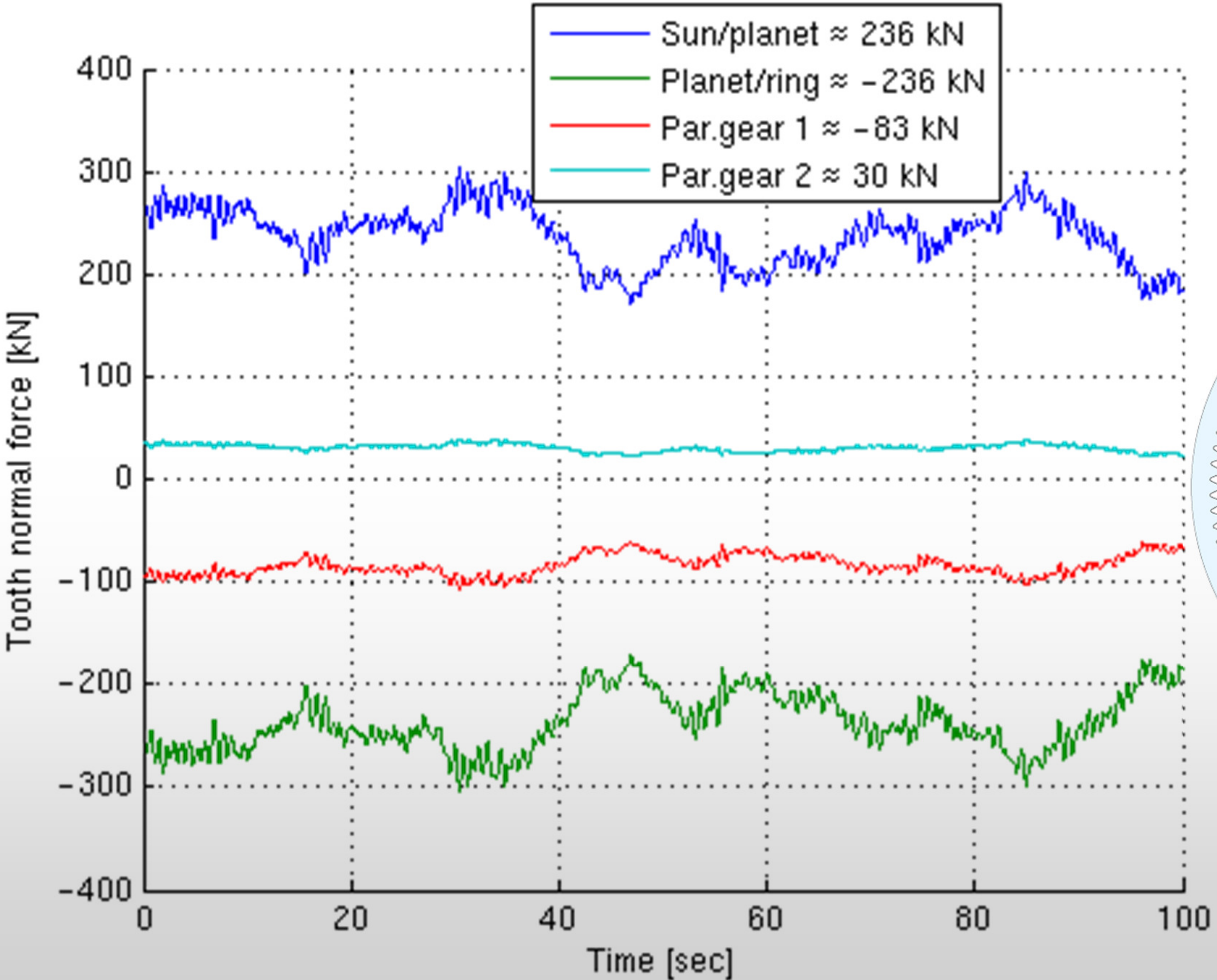
$$\begin{bmatrix} M & \Phi_q^T \\ \Phi_q & 0 \end{bmatrix} \begin{bmatrix} \ddot{q} \\ -\lambda \end{bmatrix} = \begin{bmatrix} g \\ \gamma \end{bmatrix}$$

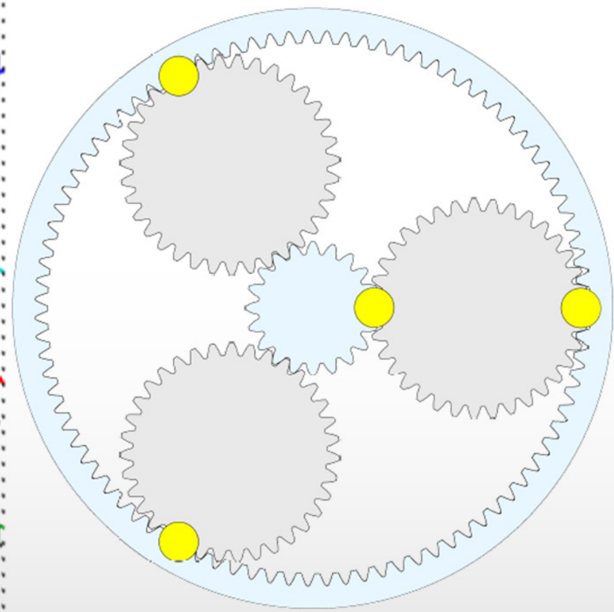
Reaction forces (in bearings/gear tooth forces etc):

$$M\ddot{q} = \sum F \quad \text{or:} \quad M\ddot{q} = \sum F_{ext} + \sum F_{react} \Rightarrow M\ddot{q} - \underbrace{\Phi_q^T \lambda}_{\substack{\text{reaction} \\ \text{forces}}} = F_{ext}$$

Used for calculating bearing and gear tooth reaction forces and moments

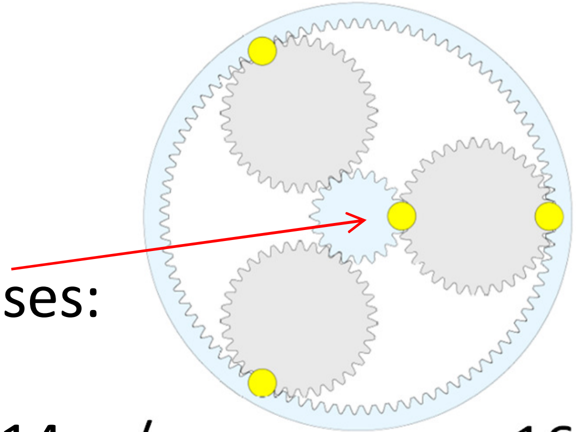
5. Results (gear tooth normal forces)



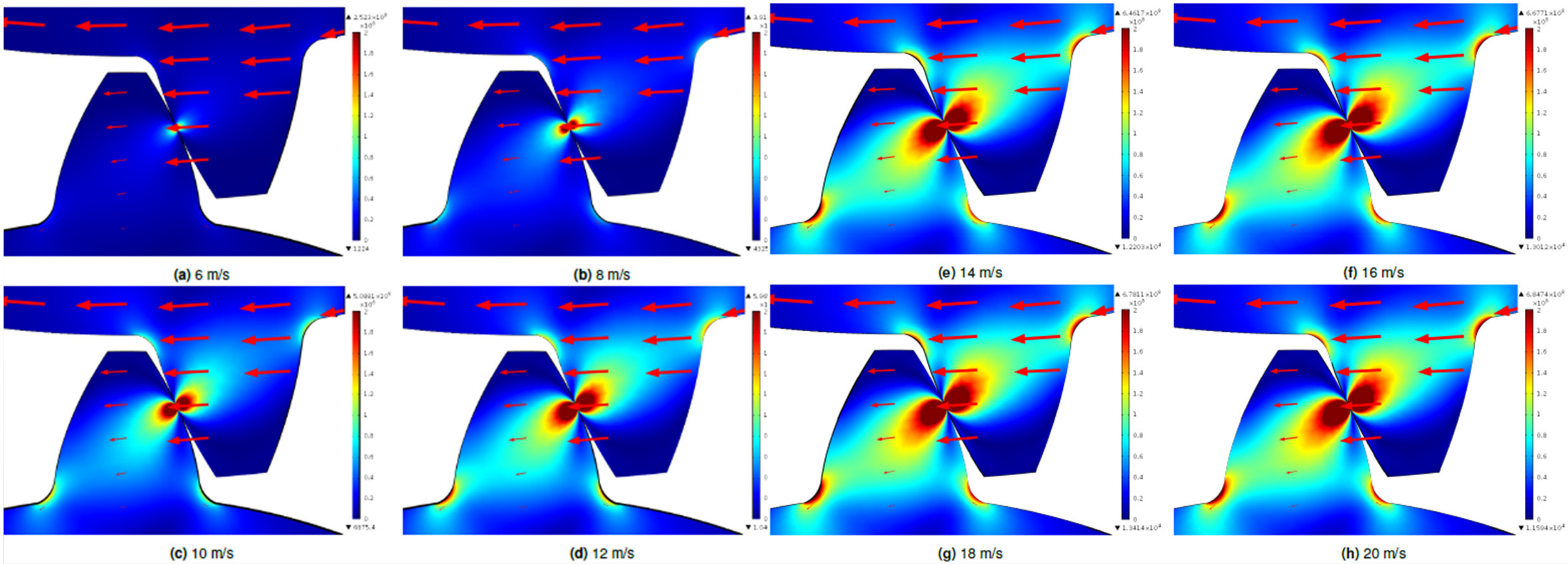


5. Results

Example: Mean sun/planet gear tooth stresses:



6 m/s　　10 m/s　　14 m/s　　16 m/s



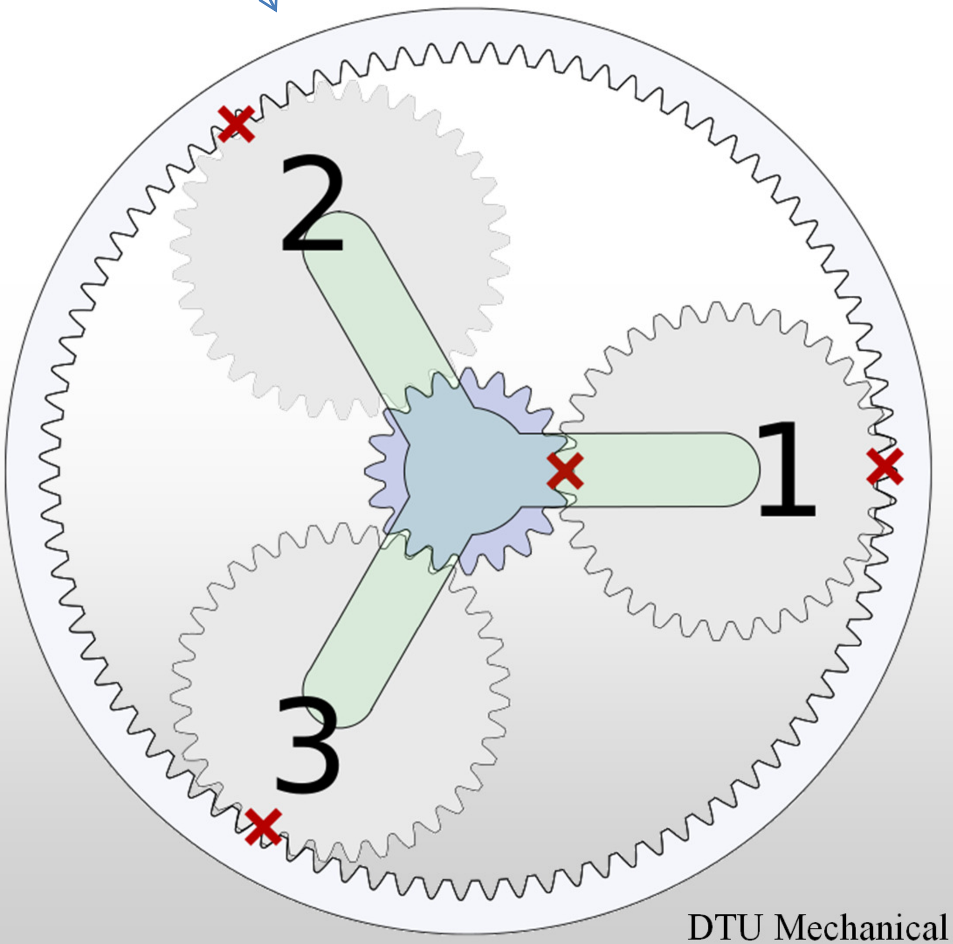
(a) 6 m/s　(b) 8 m/s　(e) 14 m/s　(f) 16 m/s

(c) 10 m/s　(d) 12 m/s　(g) 18 m/s　(h) 20 m/s

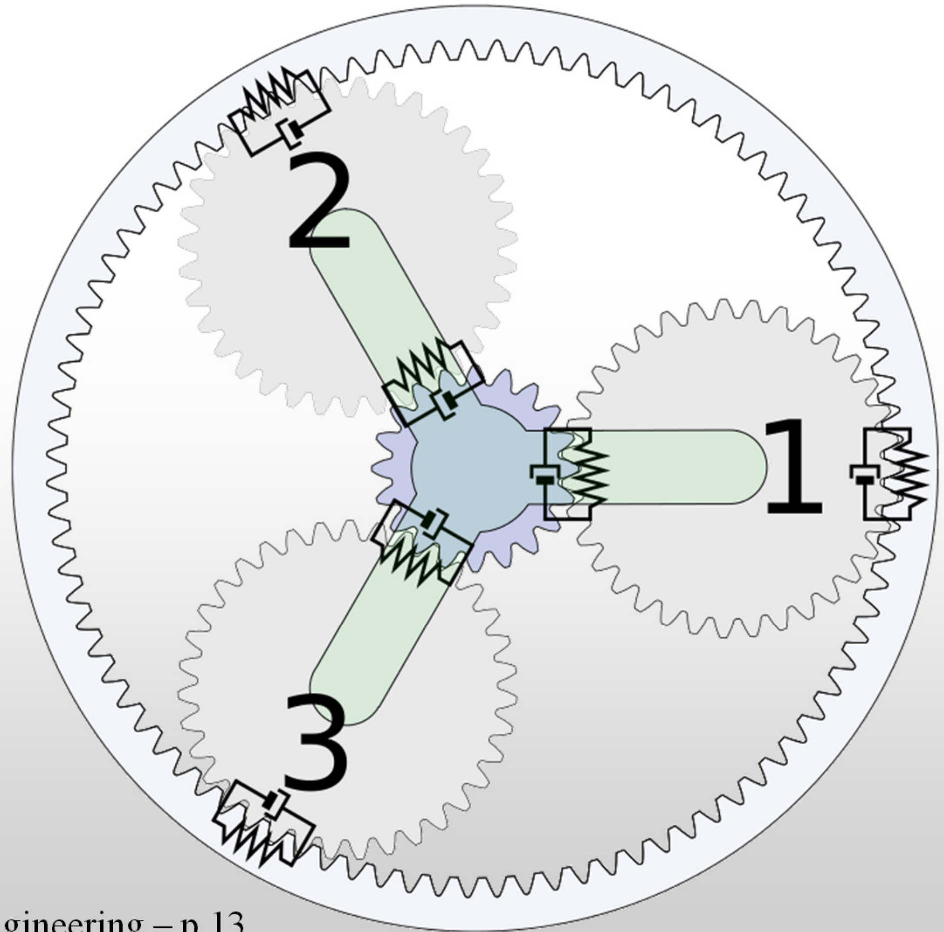
8 m/s　　12 m/s　　18 m/s　　20 m/s

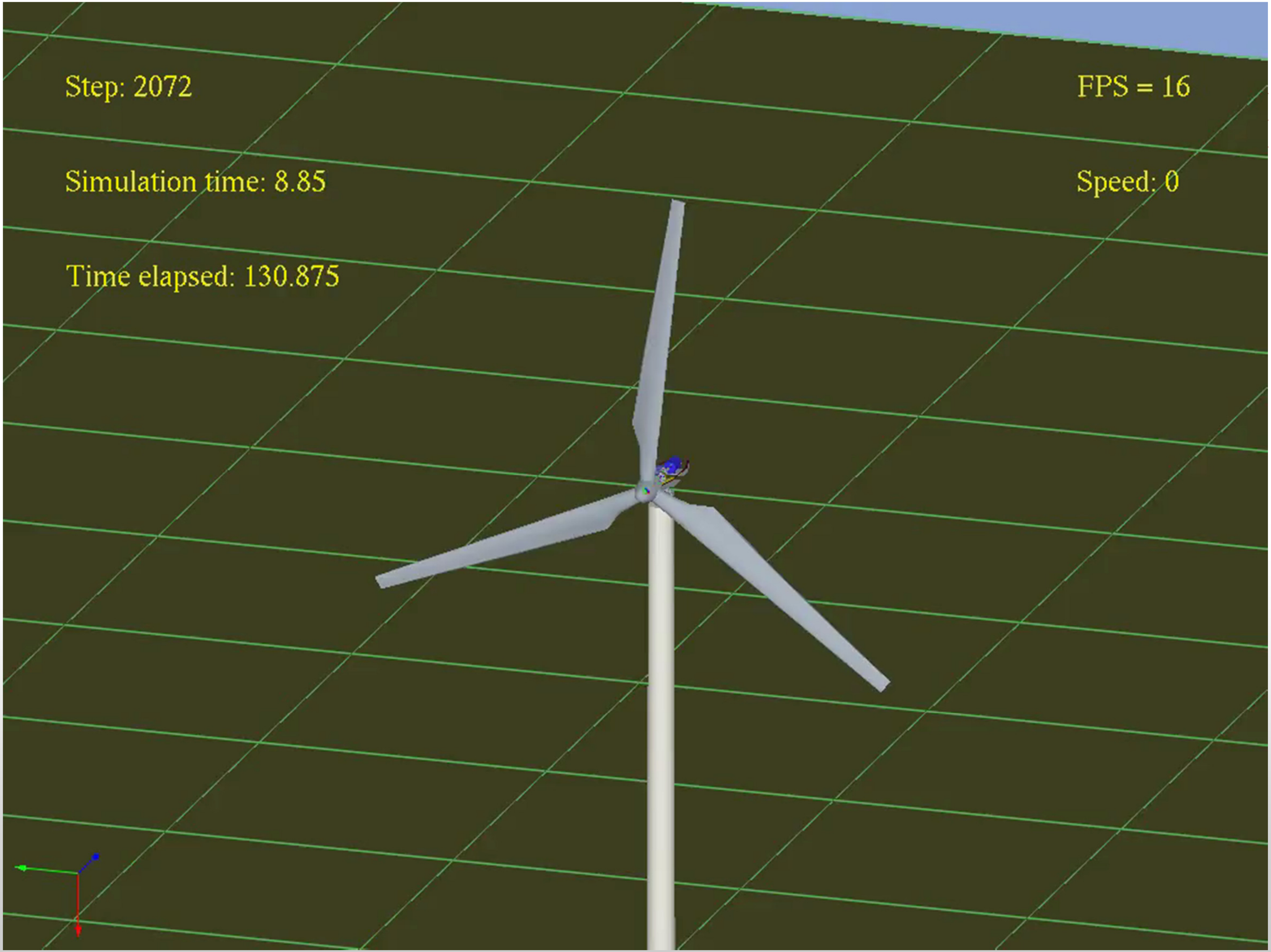
5. Results

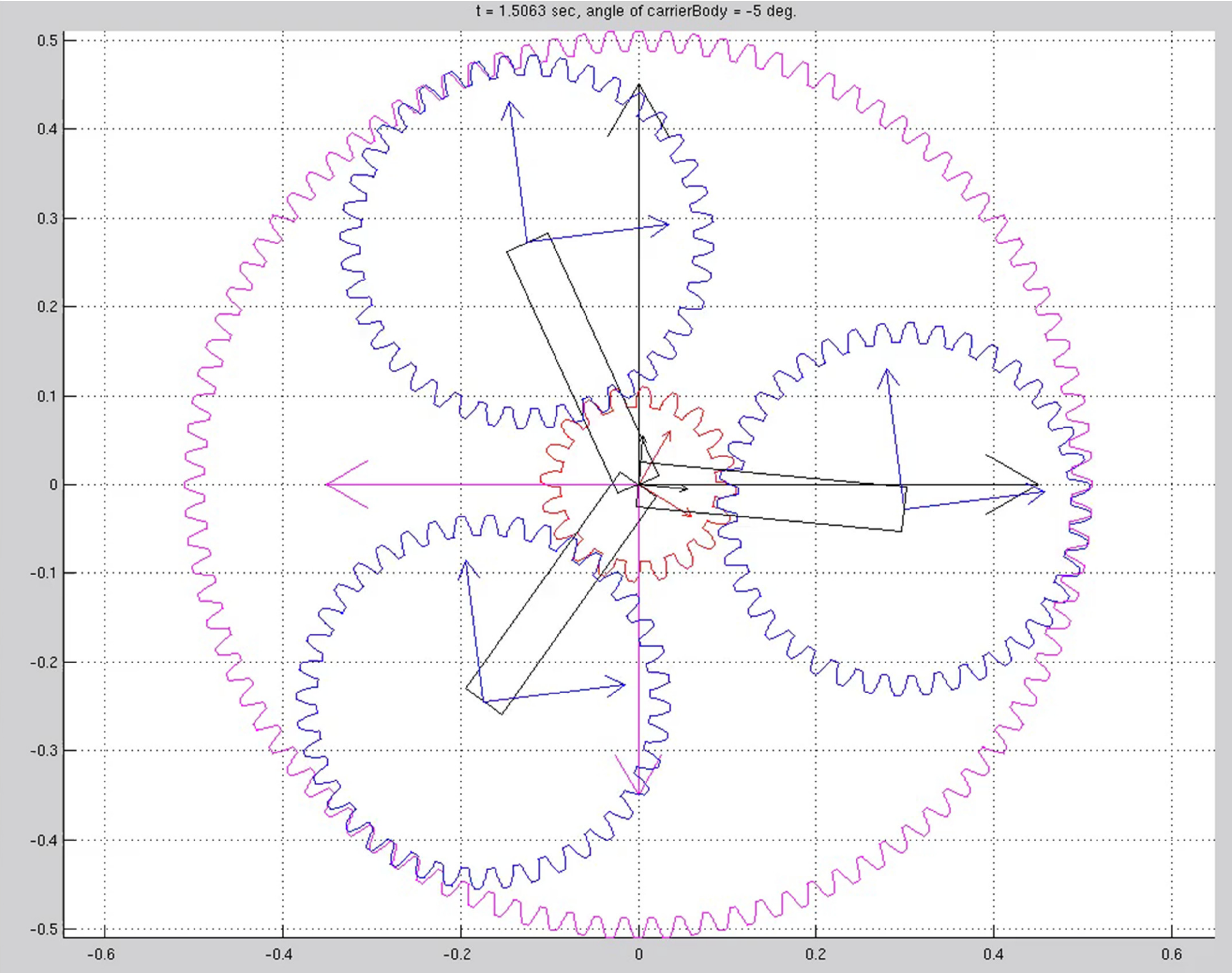
Rigid gearbox animation



Flexible gearbox animation
(work in progress)




Step: 2072
FPS = 16
Simulation time: 8.85
Speed: 0
Time elapsed: 130.875


t = 1.5063 sec, angle of carrierBody = -5 deg.
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.4
-0.2
0
0.2
0.4
0.6

6. Conclusions

- Realistic dimensions and input parameters have been used for modelling a real 500 kw windturbine and gearbox
- Input to multibody code from Flex 5 has successfully been validated using real data (wind speed + strain gauge torque + electrical power)
- A realistic drive-train multibody model has been made
- The multibody program makes it possible to extract e.g. bearing and gear tooth forces and moments (information which cannot be found with Flex 5 without modifications).
- Results from the program can easily be extracted for further analysis using FEM or other tool (e.g. FEM-model of gear tooth stresses made in Comsol Multiphysics).

Thank you for your time